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AUTHOR(S) France A. Cordova, ESS-9

Keith O. Mason, Mullard Space Science Laboratory;
Visiting Scientist, ESS-9

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Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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SHORT-TIMESCALE VARIABILITY IN CATACLYSMIC BINARIES

France A. Córdova

University of California
Los Alamos National Laboratory
MS D436, Los Alamos, NM 87545

Keith O. Mason

University College London
Mullard Space Science Laboratory
Holmbury St.Mary, Dorking, Surrey, U.K.

ABSTRACT

Rapid variability, including flickering and pulsations, has been detected in cataclysmic binaries at optical and X-ray frequencies. In the case of the novalike variable TT Arietis, simultaneous observations reveal that the X-ray and optical flickering activity is strongly correlated, while short period pulsations are observed that occur at the same frequencies in both wavelength bands.

In general, variability in these stars ranges from several seconds to a few minutes. The fastest activity yet detected occurs on a timescale of 1-3 s and is observed in two magnetic variables of the AM Herculis class. On the high end of the period distribution are a few objects with oscillation periods of 10-20 minutes; these were recently discovered as the optical counterparts of hard X-ray sources. In some cases the pulsations observed in cataclysmic binaries are very stable, with $\dot{P} \sim 10^{-12}$-10^{-14} s s^{-1}. In many such stars, however, the pulsations are not limited to a well-defined frequency. These less coherent oscillations usually occur at times when the luminosity of the system is changing. For dwarf novae, monotonic changes in the oscillation period, amplitude and coherence occur during the progress of an outburst. In the most extreme cases observed, the coherence timescale of an oscillation is only one or two pulsation cycles.

The colors of the oscillations in two dwarf nova have been measured and appear to be much bluer than any simple thermal model would suggest. It has been proposed that recombination radiation from HI, HeI and HeII might contribute to the pulsation amplitude between 3200 and 3800 Å.

Stable oscillations in cataclysmic binaries are usually considered to be indicative of the rapid rotation of a magnetic, accreting white dwarf, although in a few cases they may be due to nonradial pulsation modes of the white dwarf itself. The pulsations of the dwarf novae are thought to result from

oscillatory modes excited in the disk or in the surface layer of the degenerate star. The two second quasi-periodic variability in the magnetic stars may be caused by a thermal instability in the height of a standoff accretion shock above the degenerate star, or by oscillations in magnetic flux tubes that channel the accretion flow. The observation that in TT Ari the hard X-ray and optical flickering are correlated suggests that it is unlikely that the flickering originates in the bright spot, or mass-transfer region, on the outer disk in this star; an atmosphere around the inner disk or central star may be the site of this activity.

I. INTRODUCTION

The kinds of temporal activity observed in cataclysmic variables (hereafter, CVs) have been loosely organized as: stable pulsations (e.g. the DQ Her and H2252-035 stars), "nearly" stable pulsations (predominantly the dwarf novae during outburst and a few novalike disk stars), "not-very-stable-at-all" pulsations (all subclasses, including dwarf novae in outburst and some magnetic variables) and completely unstable pulsations (i.e. "flickering", in all stars). We shall describe examples of these kinds of activity, and illustrate that the dividing lines between coherent and quasi-coherent oscillations, and between quasi-coherent and flickering activity, are not clear, either in the observations themselves, or in the theoretical models, which may accomodate these transitions easily.

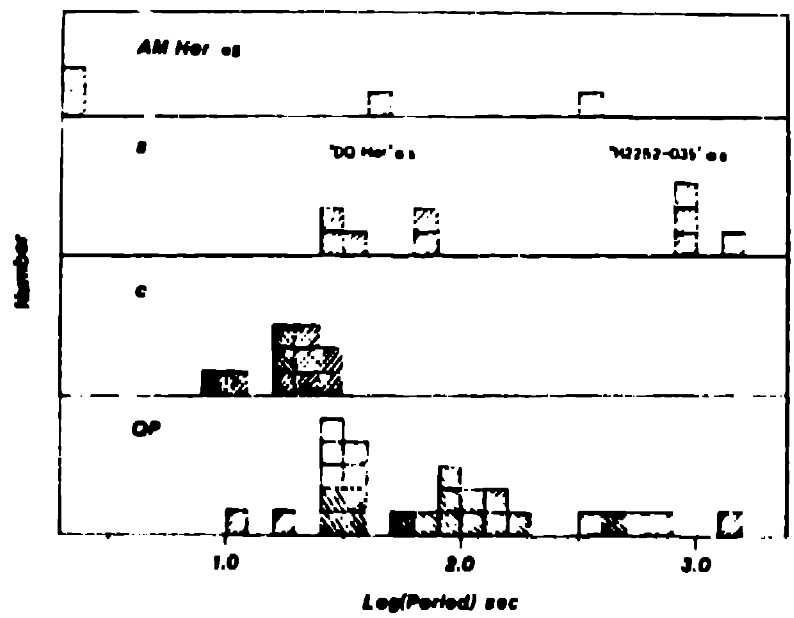

Fig. 1 Distribution of oscillations found in cataclysmic variables as a function of period. Each box represents a star; the dwarf novae are distinguished by a cross-hatched box. The oscillations have been grouped according to their coherence. Thus we have from the bottom up "quasi-periodic" oscillations" = QP; "coherent" oscillations = c; and "stable" oscillations = s. Oscillations seen in the AM Her stars are plotted separately in the top panel. If oscillations with more than one period have been detected in a star, each is included as a separate box.

TABLE I Oscillations in Cataclysmic Variables

Star	Subclass / λ band*	Period	Coherence**	Refs.
RX And	dN/V	36s	QP	[52,58]
AE Aqr	NL/V	33.078s	$\dot{P}<2.5\times10^{-14}$	[39,42]
AE Aqr	NL/V	~18,~36s	QP	[39]
AE Aqr	NL/hx	33s	?	[40]
TT Ari	NL/V	12, 32, 500–1100s	QP	[56,18]
TT Ari	NL/hx	9, 12, 32s	?	[18]
Z Cam	dN/V	16.0–18.8s	c	[51]
SY Cnc	dN/V	23.3–33.0s	c	[28,43,52]
YZ Cnc	dN/V	75–95s	QP	[43]
YZ Cnc	dN/hx	227s	?	[6]
AM CVn	td/V	26.3s	QP	[43]
HT Cas	dN/V	20.2–20.4s	c	[43]
HT Cas	dN/V	~100s	QP	[43]
V436 Cen	dN/V	19.5–20.1s	c	[65]
Z Cha	dN/V	27.7s	c	[62]
EM Cyg	dN/V	16.6–21.2s	c	[33,43]
SS Cyg	dN/V	8.5–10.9s	c,QP	[14,17,46]
SS Cyg	dN/V	32–36s	QP	[43,54]
SS Cyg	dN/sx	~9, ~12s	~20 cycles	[8,3]
U Gem	dN/V	73,146s	QP	[54]
U Gem	dN/sx	20–30s	1–2 cycles	[3]
AH Her	dN/V	24.0–38.8s	c,QP	[15,16,43]
AH Her	dN/V	~100s	QP	[43]
AM Her	MV/V	various	QP	[59]
AM Her	MV/sx	20–60s	QP	[illegible]
DQ Her	cN/V	71.07s	$\dot{P}=-9.7\times10^{-13}$	[illegible]
V533 Her	cN/V	63.63s	$\dot{P}<2.5\times10^{-13}$	[illegible]
VW Hyi	dN/V	24–32s	QP	[65]
VW Hyi	dN/V	88,413s	QP	[11,65]
X Leo	dN/V	~160	QP	[24]
CN Ori	dN/V	24.3–25.0s	c	[45]
RU Peg	dN/V	11.6–11.8s	c	[47]
RU Peg	dN/V	~51s	QP	[54,47]
GK Per	cN/V	~380s	QP	[43]
KT Per	dN/V	22.0–29.2s	QP	[illegible]
KT Per	dN/V	82,147s	QP	[54]
RR Pic	cN/V	20–40s	QP	[64]
RW Sex	NL/V	620s, 1280s?	QP	[13]
WZ Sge	dN/V	27.87s	$\dot{P}=8\times10^{-12}$	[illegible]
WZ Sge	dN/V	28.97s	$\dot{P}=4\times10^{-10}$	[illegible]
V1223 Sgr	MV?/V	13.2m	c	[57]
V3885 Sgr	NL/V	29.0s	QP	[69]
AN UMa	MV/V	1–3s	QP	[27]
UX UMa	NL/V	28.5–30.0s	$\dot{P}\sim1\times10^{-5}$	[31]
2A0311-227	MV/V	4–7m	QP	[66]
2A0311-227	MV/sx,hx	4–7m	QP	[49]
3A0729+103	MV?/V	15.2m	c	[26]
E1405-451	MV/V	1–3s	QP	[24]
H2215-086	NL?/V	20.9m	c	[45]
H2252-035	MV?/V	14.3m	c	[44]
H2252-035	MV?/hx	13.4m	c	[67]

*V = visual; sx = soft X-ray (0.1–0.5 keV); hx = hard X-ray (>0.5 keV); td = twin degenerate.
**QP = quasi-periodic; c = 'coherent'.

For convenience, the observations of all CV pulsations, including the oscillation periods and coherence times are summarised in Table 1 (from [5]) The distribution of the various oscillations with period is illustrated in Figure 1.

II. THE STABLE PULSATIONS

Until recently only a few cataclysmic variables were known to exhibit stable pulsations. These objects were DQ Herculis, V533 Herculis, AE Aquarii, and WZ Sagittae (see refs. in Table 1). The periods range from 70s for DQ Her to 28s for WZ Sge. The Q values for these stars ($=\dot{P}/p$) are about 10^{-12} s s^{-1}. While DQ Her and V533 Her exhibit only single pulsations, WZ Sge sometimes exhibits two closely spaced periods (at 27.87s and 28.97s) simultaneously; both periods have relatively high Q values. The two periods are not simply related to each other or to the 82 minute orbital period of the system. AE Aqr, in contrast, is found to pulse at both the fundamental and the second harmonic of its 33s period. This star is the only one of the four in which pulsed X-ray emission (with an effective temperature $T \sim 10^6$ K) may have been detected ([40]).

Recently several new X-ray sources have been identified with close binary systems which exhibit highly stable optical pulsations. The four such objects thus far discovered are: H2252-035, 4U1649-31 (=V1223 Sgr), H2215-086, and 3A0729+103. Their pulsation periods range from 13 to 21 minutes, an order of magnitude larger than the pulsation periods of the DQ Her variables (See Fig.1). Their periods are similar to the X-ray pulsation periods of the massive neutron star binaries X Per (13.9 m) and WRA 977 (11.4 m), which have orbital periods of greater than one month. The H2252-035 stars, however, are thought perhaps to contain accreting white dwarfs rather than neutron stars because of the similarity of their optical spectra to those of the cataclysmic variables, and their comparatively low ratio of X-ray to optical flux (<1) coupled with their orbital periods of only a few hours. The nature of the compact star will be conclusively discerned if $\dot{P}/p$ is eventually measured to be of order 10^{-10} s s^{-1}, since this would indicate that the moment of inertia of the central star is too low for it to be a white dwarf.

For H2252-035 (the only case among the four similar stars for which extensive X-ray times series are available), the X-ray pulsation period is shorter (13.4 m) than the optical pulsation period (14.3 m) [67,44]. The difference in frequency between these two pulsations is the orbital frequency of the binary (P = 3.6 hr) which leads to the interpretation of the optical pulsations as being due to reprocessing of the beamed X-ray emission from the prograde spinning central star in matter fixed with respect to the binary system. The optical reprocessing site may be the companion star and/or a bulge on the outer edge of the accretion disk ([44,12]).

III. THE NOT-SO-STABLE OSCILLATIONS

1. CVs with Luminous Disks

(a) Optical Observations: Compared to the pulsations just described, the optical oscillations that have been observed during the visual outbursts of many dwarf novae, and a few of the novalike stars, are much less stable in period and phase. These pulsations were first discovered about ten years ago by B. Warner, E. Nather and E. Robinson (see the reviews [53,63]). The oscillations have been categorized by Robinson and Nather [54] into two types:

the "coherent" oscillations with periods in the range 7 to 40 s and period derivatives of about 10^{-5} s s^{-1}, and "quasi-coherent" oscillations with periods from 30 to ~1000 s and stability over only a few pulsation cycles. Figure 1 shows the number distribution of these two types of pulsation versus period. Some overlap can be seen, but the quasi-coherent oscillations do indeed have longer periods, on average, than the "coherent" oscillations. In two cases (RU Peg and SS Cyg) both types of oscillation have been observed simultaneously in the same object [47,54].

The oscillations of the dwarf novae are only observed during their outbursts. During the course of a single outburst the "coherent" oscillation can drift smoothly in period as the luminosity changes [43,14]: decreasing at the beginning of the outburst, reaching a miniumum value near the time of maximum light, and subsequently increasing during the outburst decay. Variations in period of up to 16% have been observed over a single outburst [16] and up to 35% between different outbursts of the same star [43]. For the high inclination systems Z Cha and HT Cas phase changes are observed during their eclipses [65,43]. A model in which a collimated beam from the white dwarf is reflected from the inner disk (cf. [50]) successully fits the observed phase shifts and gives information about the inclination angle of the system. The quasi-coherent oscillations appear during the outburst decline; their frequency spread is large enough to obscure a change in period of the same magnitude as observed in the coherent oscillations. The quasi-coherent oscillation in U Gem is observed during the total eclipse of the mass transfer bright spot on the outer disk, and cannot therefore be formed at this location.

Further attempts to determine the nature of the pulsed source have concentrated on measurements of the optical colors of the pulsation. Simultaneous measurements in three colors (U, B+V, and R) by Middleditch and Cordova [28] show that the optical pulsation of the dwarf nova SY Cancri during an outburst is much bluer than any simple thermal model would allow. Hildebrand, Spillar and Steining [15] have also found that the pulsation of AH Her during outburst is extremely blue. The SY Cnc experiment indicates that, if U band measurements are not made, simultaneous V and R observations would show that the color of the variable component was red. Thus care should be excercised in interpreting narrow band or two color observations of the pulsations. Middleditch and Cordova also found that the colors of the flickering in SY Cnc are even bluer than the pulsations. Other observers have noted extremely blue flares in SS Cyg [61] and AE Aqr [39]. Walker [61] demonstrates that the flares in SS Cyg are due chiefly to enhancements in broad Balmer emission features. Middleditch and Cordova [28] have suggested that recombination radiation from HI, HeI and HeII may contribute to the pulsed spectrum; if this is the case the emission lines may also be pulsed.

It is also of interest to note that a quasi-periodic (160 s) oscillation from X Leo during an eruption was found to be extremely red in color using the same 3-channel system employed for the SY Cnc measurement [28]. The X Leo result, however, was derived from only a single short observation (in contrast to that of SY Cnc which spanned several days) and must be verified. Such differences between the colors of the pulsations among stars would clearly have important implications for any model of their origin.

(b) X-ray Observations: The short period of the coherent optical oscillations suggested a location near the degenerate star; it was expected then that the source of the pulsation would be of high energy. This expectation was confirmed when the HEAO-1 X-ray satellite made observations of several hours in duration of SS Cygni and U Geminorum during visual outbursts and detected rapid, high amplitude soft X-ray pulsations in both stars [8,3].

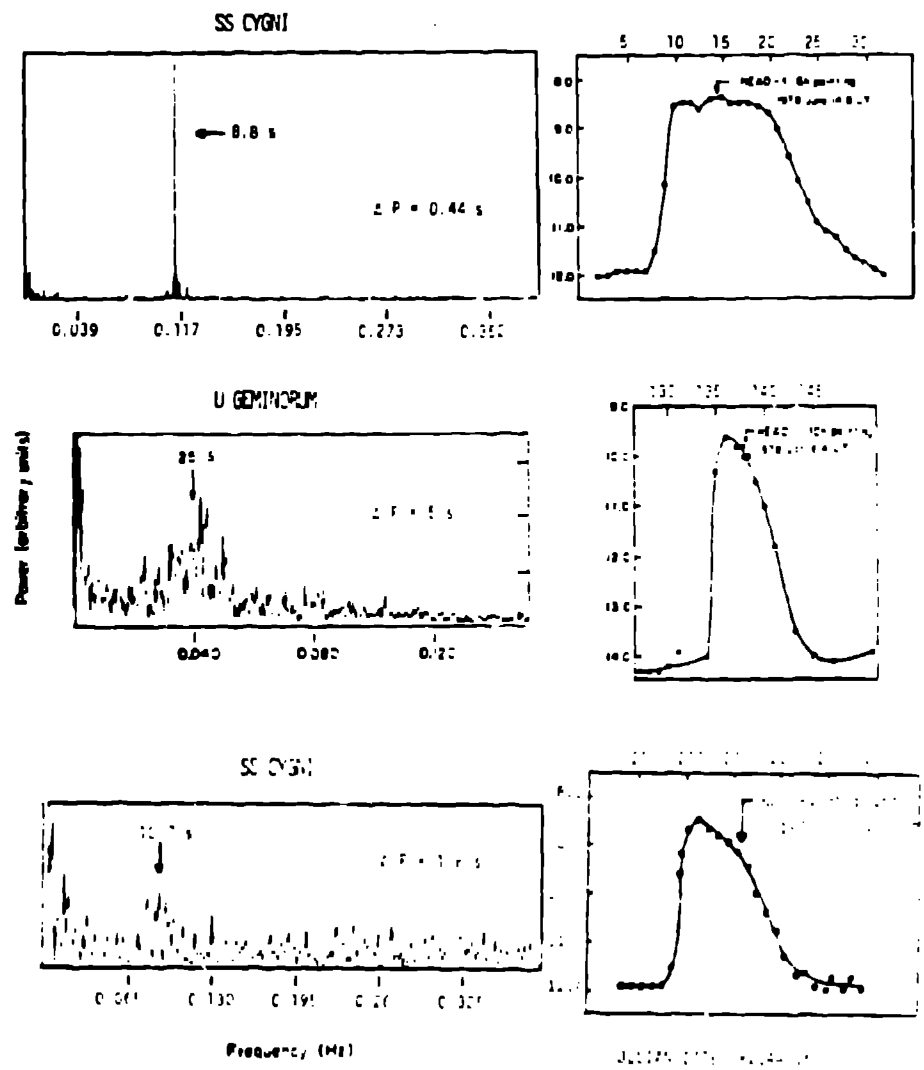

Fig. 2 The short period oscillations of SS Cyg and U Gem. Left - Power (on a linear scale) versus frequency showing the period of each oscillation. ΔP is a parameter related to the width of the period distribution and is thus a measure of the coherence of the oscillation [8,3]. Right - Optical light curves from data supplied by J. Mattei and the AAVSO show when during the outburst the HEAO-1 observations were made.

In SS Cyg pulsations were detected both times that the source was observed, once at a period of 9s and once at 11s; this is consistent with the range of periods observed for the star at optical wavelengths. In U Gem three outbursts have been witnessed using X-ray detectors. HEAO-1 observed 25s pulsations in the star, but two Einstein observations showed no evidence for pulsations [25]. However, in the latter observations fluctuations were detected on a timescale (~20 s) similar to that of the HEAO-1 pulsation. The mean amplitude of the X-ray pulsations was measured at 30% and 17% respectively in two separate observations of SS Cyg, and 15% during one observation of U Gem. The amplitude of the oscillations was such that individual pulses could easily be distinguished in the X-ray light curves. Figure 2 shows Fourier transforms of a section of data from each of the three HEAO-1 observations in which pulsations were detected. Also shown are the optical outburst light curves, upon which the time of the X-ray observation has been marked.

The temperature of this pulsed emission is a few times 10^5 K [8,23]. Only the high energy tail of this spectrum could be seen with the lowest energy HEAO-1 detector. The poor spectral resolution of the X-ray detector does not allow us to discern whether the pulsed source is fairly hot (~50eV) and very small (10^{16}-10^{17} cm^2), or if it is much cooler (~15eV) with an area about equal to the surface area of the white dwarf. The bulk of the radiation is presumably emitted in the extreme ultraviolet, but without EUV measurements neither the size nor the luminosity of the pulsed source can be determined with any accuracy.

TABLE 2 Observations of Pulsations in SS Cygni

Visual Magnitude	Period	Coherence (s)	References
Optical			
8.3	7.5	>3000	14
8.2	7.3	2000 - >3000	14
8.5	7.5	1000	14
9.0	9.0	470	14
8.5	8.2	2700	17
8.6	8.5	3900	17
8.5	9.7	>4000	46
X-ray			
8.5	8.8	160-400	8
9.3	10.9	20	this paper

One of the most interesting aspects of the X-ray observations is that the high signal to noise of the pulses permits much better pulse-timing analysis than is possible using the extremely weak optical oscillations. This analysis reveals that the X-ray counterparts of the so-called "coherent" oscillations in dwarf novae during outburst may sometimes appear as unstable as the so-called quasi-periodic optical oscillations. For example, SS Cygni's X-ray pulsation is at the same period as the "coherent" optical oscillation in that source. Yet the coherence of the X-ray oscillations is, during one observation, only about 20 pulsation cycles [8], as compared to a typical value of about 1000 cycles for the optical oscillations [43]. In the second SS Cygni X-ray observation the phase is maintained over less than two cycles (see Figure 2)! This is a tremendous range in coherence values for what appears to be the same pulsation.

Table 2 summarizes all the optical and X-ray pulsation measurements made of SS Cygni. Figure 3 is composed from these data and shows a plot of the period versus the measured coherence time. Figure 3 also shows that the coherence is not a single valued function of the period. A coherence/luminosity relationship similar to the period/luminosity relationship with its hysteresis-like behavior may be operating (that is, a maximum coherence may be reached during the course of the outburst), but additional observations (preferably of an X-ray pulsation because of its higher amplitude) through an outburst are required to test this. It is interesting to note that a pulsation with a coherence as low as that of the measured X-ray oscillations would probably not have been detectable in the optical. The reason the pulsations in the dwarf novae become unobservable toward the end of an outburst may be because their coherence decreases to the point where they degenerate into random flickering.

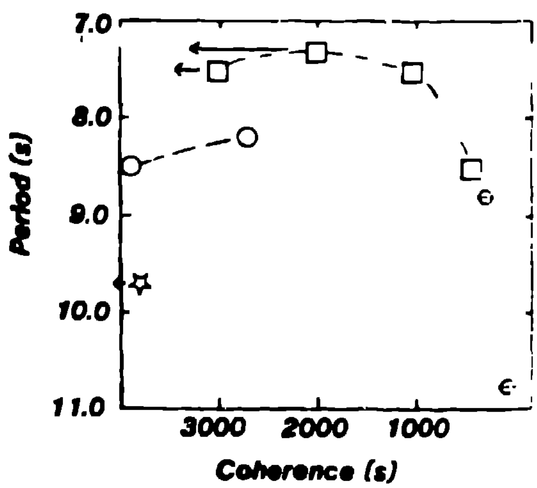

Fig. 3 Oscillation period versus coherence timescale for all optical and X-ray observations of SS Cyg from data in Table 2. Dashed lines connect observations made during the same optical outburst; arrows signify upper limits. The symbols denote different references; see Table 2.

(c) Simultaneous Observations: The novalike variable TT Arietis has yielded the first long, simultaneous, continuous X-ray and optical observation of a star of this kind [18]. Unlike the very soft X-ray variability just described for SS Cyg and U Gem, in TT Ari the X-ray emission detected is quite hard ($T_{effective} \sim 2 \times 10^8$K). Both the hard X-ray and the optical data show the presence of short period oscillations at periods of 12s and 32s, with amplitudes in the X-ray of ~20% and in the optical of ~1.5%. This is the first detection of oscillations in hard X-rays (note: the possibly pulsed X-rays in AE Aqr have a temperature of about 10^6K, much softer than those of TT Ari). The coherence of TT Ari's pulsations is not known, but, in the simultaneous optical data they appear to occur at random times and are not detected for more than ~ 4000s at a time. In the optical, the two periods were observed during the same ~4000 second time interval.

2. The AM Her Stars

One of the ubiquitous properties of the AM Her class of magnetic variables is high amplitude variability on a large number of timescales ranging from seconds to minutes. The flickering behavior of AM Her itself has been studied extensively at both optical and soft X-ray wavelengths, as summarised by Tuohy et al. [60]. The variability can generally be approximated well by randomly occuring pulses of flux (i.e. shot noise). However, several instances of short sequences of equally spaced pulses have been found in the soft X-ray band, suggesting that the 'shots' may consist of pulse trains rather than isolated bursts [60]. The decay time of the autocorrelation function of the optical flickering is on average broader than that of the X-ray data, with the time lag at which the strength of the correlation reaches 1/e of its maximum value being typically 20-60 seconds in the broadband optical light and 7-12 seconds in the soft X-ray band. Szkody et al. [59] find that there is no correlation between the short timescale variability of simultaneous optical and soft X-ray data. They suggest that if the magnetic field of AM Her has a dipole configuration one pole may be the source of the optical variability and the other pole the source of the X-ray fluctuations.

A different and much shorter timescale variation has recently been identified in the optical light of two AM Her stars. The effect was first noticed as a broad excess in the power spectrum of the newly identified AM Her variable E 1405-451 at periods between about 1 and 3s [24], indicative of quasi-periodic variations on this timescale. This is the fastest quasi-periodic phenomenon yet observed in a cataclysmic variable. The optical flux of E1405-451 must vary by 1.2% rms to produce the level of noise measured in the power spectrum. The noise is not produced during any one section of time or orbital phase, and is approximately a constant proportion of the net optical light throughout the orbital cycle. Middleditch [27] has examined high time resolution optical data on several other AM Her stars. He finds similar quasi-periodic variations in the light of AN UMa, with a similar range in frequency, but about twice the amplitude relative to the steady emission found in E1405-451. This behavior was also searched for in four other stars, AM Her, EF Eri, VV Pup and PG 1550+191, as well as in AN UMa during its low state, but not found. Upper limits to the percentage rms variation range from 0.25 % for AM Her in its high state to 1.3% for both AN UMa and AM Her in their low states. In addition, Tuohy et al. [60] found no evidence for high speed quasi-periodic behavior in the soft X-ray flux of AM Her down to frequencies of 40 ms. Further observational data is required to determine if the occurence of the phenomenon is related to any particular state of these stars.

IV. FLICKERING

There are many ways in which a stable pulsation can manifest itself as unstable if it suffers random amplitude and/or phase changes. The degree of randomness -- its frequency and the timescale over which it occurs -- can cause a bewildering array of apparently different types of activity. For example, as illustrated in [3], a constant underlying period can be masked in a power spectrum if the phase of the pulsation is disturbed in a random manner. This is one way of producing apparently quasi-periodic behavior. In the limit as the phase noise is further increased, the number of cycles over which the pulsation is coherent becomes less than one, and it no longer makes sense to speak of a pulsation. Rather, we call this behavior flickering.

Flickering on a timescale of minutes is a common property of the optical light of cataclysmic variable systems. Recently it has become possible to examine the short timescale variability of both the hard X-ray and (when present) the soft X-ray flux of a number of systems. It is found, based on observations with the Einstein satellite which were typically ~2000 s long, that many of these stars exhibit X-ray flares during which their fluxes increase by 2 - 3 times. On average, the flares last for 100 - 500 s and their recurrence times are only a factor of one or two times longer than their duration [6]. The timescales for X-ray variability are very similar to the timescales for optical variability.

In the case of the novalike star TT Arietis, it has been possible to demonstrate a physical connection between the X-ray and optical flickering. This star is known to exhibit marked optical variability on a timescale of 800 - 1000 s [56]. Extensive simultaneous X-ray and optical fast photometry on TT Ari [18] demonstrates that its hard X-ray flux is also variable on the same timescale and that this variability is highly correlated with that in the optical band. There is, however, a time lag in the correlation, with the optical var ons <u>preceding</u> those at X-ray wavelengths by an average of 60 s. This is the first observation of optical activity initiating X-ray activity, instead of vice-versa as would be expected if reprocessing were responsible for the correlation. The fraction of the total light that is variable is significantly higher in the X-ray band (0.1 - 4 keV) than in the optical band (3700 - 5600 Å): the luminosity ratio of the flickering component, $(L_x/L_o)_{flickering} = 0.5$, while the ratio of the total emission, $(L_x/L_o)_{total} = 0.1$.

V. MODELS

We now describe some of the models proposed to explain the origin or nature of the diverse temporal activity in CVs.

1. <u>Rotation, Pulsation</u>

The stable oscillations of the DQ Her stars are most often interpreted as the rotation of the beamed radiation pattern from the magnetic poles of an accreting compact star (see e.g. [19,38,39]). Rotation has traditionally been favored over pulsation of the white dwarf as the driving mechanism for the pulsations of DQ Her in particular, although there is no conclusive observational evidence for a magnetic field in this star [7]. On the other hand, the double period exhibited by WZ Sge may be interpreted more easily as pulsation rather than rotation; non-radial g-mode pulsations have been proposed by Robinson, Nather and Patterson ([55]; but see also [41] for arguments favoring rotation in this star).

Rotation is also the preferred mechanism for the X-ray emitting H2252-035 stars. Hard X-radiation is thought to be produced from near the base of the accretion column in the shock that is formed when the accreting material falls onto the degenerate star [20]. The X-ray pulsation period then reflects the rotation rate of that star. The second, longer period pulsation that is observed at optical frequencies is the reflected pulsation from the companion star and/or a bulge on the outer disk [44,12]. Two neutron star binaries with relatively low luminosity companions, Herculis X-1 and 4U 1626-67, also exhibit periodicities in their optical light at frequencies which are shifted from that of the underlying X-ray pulsation by an amount corresponding to the orbital frequency [29,30]. Again, reprocessing of X-ray pulsations in orbiting material is thought to be the cause. None of the H2252-035 stars has yet revealed the optical circular polarization common to the magnetic, AM Her class of cataclysmic variables. The field strengths of the latter are found to be a few times 10^7 Gauss (see refs. in [5]). A somewhat weaker field strength in the H2252-035 stars would not be detectable with current optical polarimeters; it is possible however that polarization from a $\sim 10^6$ Gauss field may yet be detected in the infrared. The probable presence of at least a partial disk in the H2252-035 systems further impairs the detection of polarization because of the diluting effect of the disk light.

2. The Oscillations in the Disk Accreting Stars

Various models, or suggestions, have been proposed to explain the nature of the pulsations of the dwarf novae and novalike objects. (See the reviews by Papaloizou and Pringle [34] and Patterson [43]). Some of the more interesting suggestions are:

(1) Rotating hot spots in the disk; these might be caused by turbulent or hydromagnetic instabilities in the accretion flow. While structure might be expected in such a flow, neither the supersonic conditions encountered near the disk boundary layer, nor the temperature and density regimes of interest have been sufficiently studied to develop a mathematical model for such instabilities. It has been estimated that the shearing time for hot spots in the disk is relatively short ($\sim 10^3$ s; [1]) compared to the lifetime of the coherent pulsations, but this timescale is easily compatible with the quasi-periodic decay times.

(2) Adiabatic oscillations in the disk. The frequencies of the oscillations of an annulus of the disk is of the order of the Keplerian period of the annulus; as shown by Cox [9], this result is independent of the detailed structure of the disk. This idea has been invoked by Robinson and Nather [54] to explain the quasi-periodic oscillations of the dwarf novae because of the corresondence of the oscillations periods to Keplerian periods in the disk, and the correspondence of the decay times to the proposed shearing time for disk inhomogeneities. The increased mass flow during the onset of the outburst could trigger this activity.

(3) Pulsations in a thin surface layer on the degenerate star. Papaloizou and Pringle [34,35] investigate the oscillations of a rapidly rotating white dwarf and find that a combination of rotation, or Rossby, modes and g modes having the periods and coherence times of <u>all</u> the observed pulsations (i.e. "coherent" as well as "quasi-coherent") could be excited on the white dwarf through interaction with the disk. Thus both types of oscillation may arise in the star itself.

To understand the nature and the exciting mechanism of a pulsation, and to determine whether the various types of pulsation have a common origin, it is of interest to study and define the noise properties of the pulsations. For the soft X-ray pulsation of SS Cyg [8] and the quasi-coherent optical oscillation of RU Peg [47], it is found that the variance of the phase of the pulsations about a constant period increases approximately linearly with time. This is consistent with a random walk in the phase of the oscillation [8]. We have measured the power spectrum of the phase and amplitude modulation for the X-ray pulsation in SS Cyg (as per the method in [30]). This confirms that there is a large component of phase modulation. However, amplitude modulation (as suggested in [14]) can be excluded as the source of the quasi-periodic behavior.

One kind of mathematical description that produces apparent shifts in the phase of an oscillation is the "second-order autoregressive process" used by Robinson and Nather [54] to model the behavior of the optical quasi-periodicities. The mechanical analogue of this process is a damped harmonic oscillator exited by random, small dispacements. Such a model also is fitted successfully to the "coherent" optical pulsation of SS Cyg by Hildebrand, Spillar and Stiening [14]. The power spectrum of an oscillation produced in this way is essentially the Lorentz function; the width of the fitted function is a measure of the coherence and the centroid a measure of the frequency of the pulsation. An autocorrelation is another method of determining the pulse parameters. A related mathematical method which gives a more accurate measure of the amplitude and decay time, but is possible only when the pulse amplitude is high, is the superposition technique described in [2].

A second way in which "phase noise" may be produced is if the phase of a strictly periodic clock is disturbed in a random manner [3]. Power spectra similar to any of those observed may be produced simply by varying the severity of the phase jitter.

A third way to produce apparent shifts in phase might be through the superposition of a number of oscillations with closely spaced periods (i.e. high order ℓ modes, as proposed in [34,35]).

More detailed information on how the period, amplitude and coherence of the pulsation are related to each other and to the luminosity is required to distinguish between these disparate models. The best source of such data would be extensive observations of the high amplitude X-ray pulsations over the entire course of a dwarf nova outburst.

3. The Variability of the AM Her Stars

A number of mechanisms could conceivably give rise to quasi-periodic oscillations in the magnetic stars. One is oscillations in the magnetic flux tubes that convey the accreting matter onto the surface of the white dwarf. This mechanism was originally suggested by Tuohy et al. [60] as an explanation of the 30 s pulse trains observed in the soft X-ray flux of AM Her, but might, in certain parameter regimes, also give rise to oscillations with a period of a few seconds or less as observed in E1405-451 and AN UMa. A second model is based on a thermal instability in the height of the standoff shock above the magnetic pole of the white dwarf. Such an instability was discussed by Langer, Chanmugam and Shaviv [21] for the case where bremsstrahlung radiation dominates the cooling of the post shock region, and predicts oscillation periods of about 2 s for reasonable values of the stellar mass, magnetic field strength and accretion rate. Since the oscillation period is a function of the accretion rate, variations in this rate (which may also cause the large amplitude flickering of these stars on timescales of minutes) may generate the observed breadth of the power spectrum peak in E1405-451 and AN UMa. Middleditch [27] has attempted to test this by searching for a correlation between the instantaneous pulsation frequency and the source intensity of E1405-451, corrected for the orbital modulation of that star. The results are consistent with those expected from the model, but are not unequivocable.

4. The Origin of the Flickering

Optical flickering in the non-magnetic cataclysmic systems is usually associated with the mass transfer bright spot on the outer edge of the disk; more than a decade ago Warner and Nather [66] demonstrated this to be the case for U Gem, but there is little more than 'argument by analogy' to support a similar origin for the flickering in all CVs. The observation in TT Ari of simultaneous optical and X-ray flickering conclusively demonstrates a physical link between the X-ray and optical variability in this star. It implies that optical flickering may arise in a location other than the bright spot, since the bright spot is an unlikely site for producing substantial hard X-ray emission.

In the AM Her stars the high amplitude optical flickering is believed to originate in the magnetically funneled accretion columns. Therefore, one possibility is that in TT Ari, too, a magnetic field somewhat smaller than that of the AM Her stars disrupts the disk and force matter radially onto the magnetic poles of the white dwarf. Jensen et al. [18] have examined this possibility and others for the origin of the optical and X-ray variability in TT Ari. A second interesting hypothesis proposed by these authors is that the flickering might arise in an accretion disk atmosphere, or "corona". Vertical energy transport by acoustic waves or MHD waves in an accretion disk could generate such a hot corona, although it is not yet known whether this mechanism could work efficiently in a gas pressure dominated disk. In this scenario the optical flares drive disk oscillations which in turn drive pulses of energy away from the disk plane. As they propagate into the less dense medium above the disk, the waves are amplified, and dissipate their energy in coronal shocks. The 60 s X-ray delay time is consistent with the acoustic travel time from the disk to the corona. The characteristic disk oscillation period predicted by such a model (cf. [22]) is determined by the ratio of the disk thickness to the sound speed; these periods are similar to the short period oscillations of 12 and 32 seconds observed in TT Ari. There is evidence from the ultraviolet P Cygni lines observed in the spectra of luminous disk accreting CVs that vertical energy transport does occur in the inner acretion disk [10,4], but it is not clear how the UV wind and X-ray emission are related.

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